



Prestressed Masonry for Reservoirs: A Project of the Engineer Eduardo Torroja

Joaquín ANTUÑA¹

ABSTRACT

The project of prestressed reinforced concrete structures meant, in general, the use of one of the systems protected by the patents available. Now, the use of prestressing is very common but fifty-five years ago this technique was quite expensive, due to the fees that had to be paid for the use of a system protected by a patent. In the 50's Eduardo Torroja started some research dedicated to finding a way to build prestressed structures without using a patented system. One of his solutions consisted in building a masonry brick wall reinforced with the usual steel bars and, as a result of a special method used for its construction, he achieved a compressed concrete layer that makes it possible to have a waterproof wall for building a water reservoir. Following his system, Torroja designed a reservoir built in Madrid that still exists but is not in use.

KEYWORDS

Reinforced masonry, Reservoir, Prestressed.

1 INTRODUCTION

The development of prestressed concrete opened up new possibilities for reservoir construction. Before the generalization of prestressing, the usual way to build this kind of structure consisted in reducing the tension in which the steel worked in order to prevent the apparition of cracks in the concrete. An increase of steel consumption was needed in this case, and the use of steel bars of high resistance did not improve the situation.

When in the 50's the Spanish engineer Eduardo Torroja was requested to modify the project of the reservoir in Fedala (a little town near Casablanca in Morocco), the French engineer who designed the project employed the usual method in use at that time. A reinforced concrete shell was designed for the reservoir wall; an inverted cone was the shape chosen and, following the usual procedure, the reinforcing of the concrete wall was calculated, reducing the maximum tension to values compatible with the need for absence of cracks in the concrete.

The project had started to be built and the pillars with their foundations had been erected when Torroja was requested to design a new project for the reservoir. So, the new solution needed to be prepared in a short period of time and Torroja did not have the chance to research new solutions. For this reason, he adopted the new way of building reservoirs using prestressed concrete. A thin layer of prestressed concrete was designed with the shape of a hyperboloid of revolution in which the prestressed bars were placed following the direction of its straight generatrix. The bottom of the reservoir was built in reinforced concrete using a thin masonry timber vault as a formwork. The cover was also built using two concentric timber vaults with the shape of a torus, Fig.1.

The reservoir was completed in 1955 and is still in use. But when Torroja talked about this project [Torroja 1955] he said that it was a failure. He confessed that he did not have time to look for a different solution and he

¹ Universidad Politécnica de Madrid, Escuela Técnica Superior de Arquitectura de Madrid, Avda. Juan de Herrera, 28040, Madrid, Spain, joaquinfrancisco.antuna@upm.es

used the prestressed technique because he was not capable of finding different ways to build a waterproof wall. In his opinion the project was a failure because the cost of prestressing was so high that the final price of the work was several times higher than the price of the work using reinforced concrete that had not been prestressed.

After designing the Fedala reservoir, Torroja proposed other different ways to build a prestressed waterproof wall. One of these methods consisted in the use of a reinforced brick masonry wall built in such a way that it was given waterproof qualities.

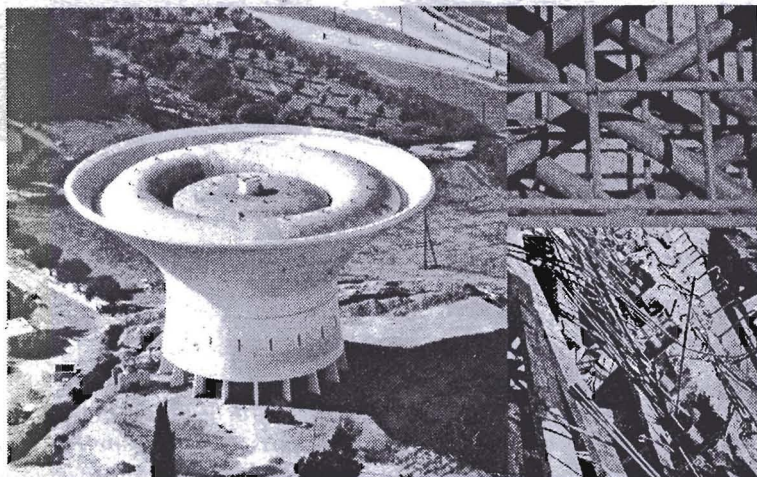


Figure 1. The reservoir in Fedala; Casablanca, Morocco. The reservoir wall was made with a prestressed concrete layer and the cover consisted in two concentric torus timber vaults. On the right you can see the prestressed “Barredo” system used to build the wall.

2 THE FIRST PROJECTS OF PRESTRESSED MASONRY

In June 1957 Torroja designed the first reservoir in which he proposed the new system to build a waterproof wall without any patented system for prestressing. It was the “reservoir for the Société Marocaine,” which was project number 837 in the files of his Technical Office. In this project Torroja worked with a French entrepreneur who works in Morocco, and they presented this project when invited to tender by the Moroccan government. In those cases, the public administration presented a project and invited offers to build it. The usual way to build a reservoir at that time was to use reinforced concrete reducing the tension of the reinforcement. The project proposed by the government is shown in Fig.2.

The proposal presented by Torroja to the government consisted in three different solutions for the same building; one of them is for building the official project in reinforced concrete that consists in a reinforced concrete wall designed with a maximum tension of 73N/mm^2 for the steel reinforcement. The other two alternatives consisted in a new solution for constructing reservoirs: The reservoir wall is designed to be built in prestressed reinforced brick masonry. The innovation consisted in how the wall is built so as to have the wall prestressed without the use of patented systems. The innovation consisted in a new construction way that allows to have a masonry wall prestressed using usual reinforced steel bars. For this first reservoir Torroja proposed two different shapes for the building. One of them had the shape of a cylinder and the other the shape of an inverted truncated cone. We will discuss this last solution.

2.1 Description of the Project

The solution in reinforced brick masonry consisted in an inverted truncated cone made of brick masonry. In Fig.3 the cross section of the reservoir is shown. The reservoir is located in the upper part and its wall consisted in three layers as shown in Fig. 3 on the right. The external one is brick masonry 25 cm thick, reinforced with some of the usual steel bars in every three bed joints; the second layer consists in a concrete wall made with selected gravel which was injected with special mortar with non shrink quick hardening cement, the injection being made after the third interior layer was made; this third layer was a brick masonry wall 25 cm thick. The lower part also has the shape of a cone and is made in brick masonry as well. In this case, the wall has only one layer of brick also reinforced with steel bars. The chimney that allows access to the reservoir is supported by the

dome which forms the bottom. This dome is made in reinforced concrete with its edges supported by a ring of reinforced concrete in the external wall. The external wall continues to the ground right down to the foundations.

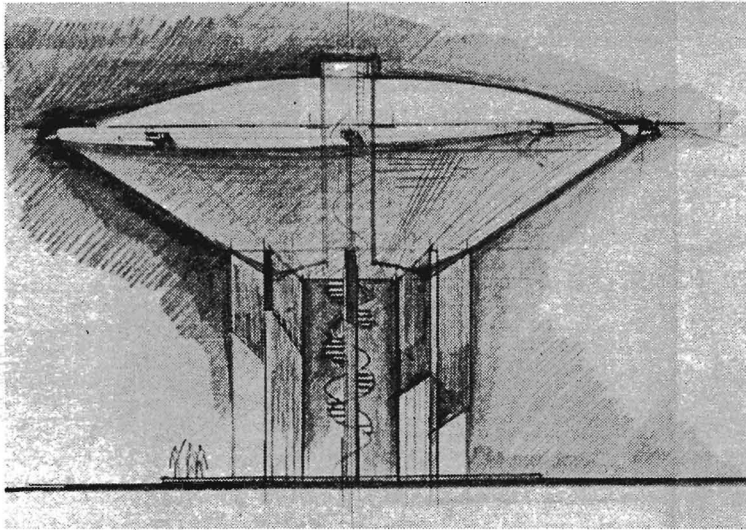


Figure 2. The project proposed by the government. The drawing is an elevation in which a cross section is designed. The wall structure consists in an inverted truncated cone made of reinforced concrete, built in at the bottom of the pillars. The bottom of the reservoir is a reinforced concrete dome with a hole where a chimney was placed. The cover of the reservoir was a dome supported by a ring on the edge of the reservoir wall.

2.2 Description of the Construction Procedure

The project description includes an explanation of the way the wall needs to be made in order to make sure that the reservoir wall is impermeable.

The brick masonry needs to be built first, the lower part and the two layers in the upper part. At the same time that the interior brick layer is made, the space between both brick walls is filled with carefully selected gravel. When the masonry is finished and the intermediate layer full of gravel, both the reservoir and the part full of gravel are filled up with water. At this moment, the external layer is under tension and some cracks may even occur and some water may leak out. If this happens, more water needs to be put in to maintain the same level. The internal wall undergoes a light compression as a result of the difference between the pressure of water in the reservoir and the pressure due to the flooded gravel placed in the intermediate layer. At this moment the injection starts. The injection starts from the lower part and in a tier not higher than 200 cm put in series of 50 cm more or less. The pressure due to the higher density of the mortar in comparison with the pressure due to the water produces the strain of the reinforcement placed in the external brick layer and, at the same time, the increase of the compression of the interior layer. When the mortar starts to set, the hydrostatic pressure effect disappears and the reinforced bars in the external layer which are under tension and have suffered a strain, tend to reduce their length and cause the concrete wall to be compressed.

To sum up, the process has two steps, first water pressure produces a strain in the external reinforced bars, then the mortar injection in the intermediate layer increases the strain, but when the mortar starts to set the reinforced bars tend to recover their initial length and compress the concrete wall. As a result, even with the reservoir full of water, the wall of the reservoir undergoes compression and the impermeability is ensured.

The construction system has, at least, two important facts to be controlled. One is the speed at which the injection needs to be made and the other, to control the time it takes for the mortar to start to set. These two variables are related.

For the analysis it was presumed that the mortar starts to set in three hours and the injection was made in tiers 50 cm high maximum and no faster than 1m high every one and a half hours. So, in three hours, when the mortar started to set, the maximum pressure was equivalent to 2 m of hydrostatic concrete pressure.

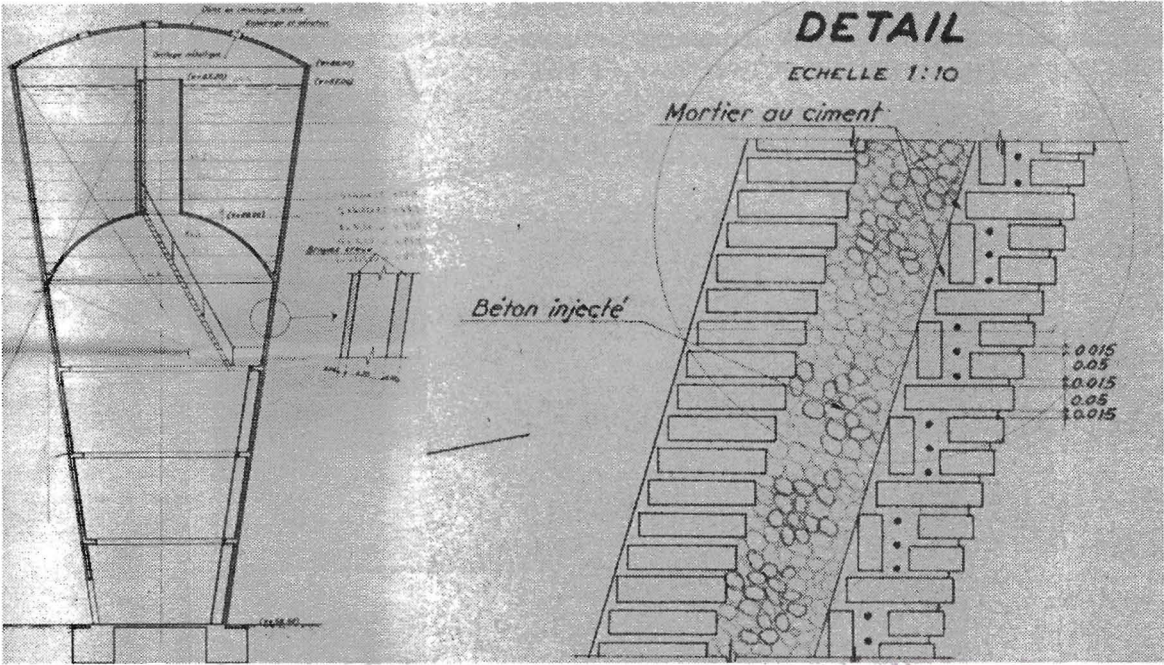


Figure 3. Cross section of the proposal made in reinforced brick masonry. The construction shape is an inverted truncated cone, built with brick masonry. The lower part is the support of the reservoir and consists in a single layer of brick work. The reservoir wall at the top consists in a three layer wall. The cover consists in a dome built with a timber vault. The detail of the reservoir wall is shown on the right. The cross section shows its three layers, the right-hand layer is the external one and consists in a brick masonry wall 25 cm thick with the reinforcement needed for every level; the left-hand layer is another brick masonry wall without reinforcement. Between these two layers some selected gravel is placed and, when the two brick walls were finished, some special mortar made with nonshrink cement was carefully injected from the bottom.

2.3 The Analysis of the Vat

2.3.1 The analysis of the bottom dome

The bottom of the reservoir was a reinforced concrete dome with a hole on the edge of which stood a chimney. This chimney was a vertical cylinder 2 m diameter, which allowed the reservoir to be inspected. The dome was analysed like a membranc and due to its dimension, the shell was under compression in all directions. The dome is supported by a ring in reinforced concrete placed on the external brick masonry. On this ring rests the reservoir wall.

2.3.2 The analysis of the external layer in reinforced brick masonry

To analyse the wall of the reservoir, it was regarded as a rigid membrane and no bending moments were taken into account. To find the size of the reinforcement three different loads may be considered: the pressure due to the water weight, the pressure due to the injected mortar and the component due to the self weight of the external brick masonry layer. In a surface of revolution we know that

$$\frac{N_{\varphi}}{r_1} + \frac{N_{\theta}}{r_2} = P \tag{1}$$

and, in this case $1/r_1=0$ and

$$r_2 = r_0 + y \operatorname{tg} \alpha \tag{2}$$

where r_0 is the radio of the basis of the truncated cone, y is the height of the considered point from the base and α is the wall inclination from the vertical, we found that

$$N_g = r_2 P \quad [3]$$

where P depends on the density of the material whose pressure we are considering, ρ is the density of the material considered (water, brick masonry and the concrete formed by the gravel and the injected mortar), d is the total height of the liquid.

In the analysis of the project the solicitations N_g were not considered since they have a small value and the N_g compression works like a prestress, helping to equilibrate the transverse bending moments.

3 THE FOLLOWING PROJECTS

Using the same construction technique, Torroja designed many reservoirs in the following years. None of these projects were built using reinforced brick masonry, but using the prestressed concrete technique. When an offer was tendered, Torroja prepared three or four different proposals. The first one was the client's solution and the others were alternative options that have been studied by Torroja trying to find cheaper and easier to build ones.

The next project designed with this system was a reservoir with a 2000 m³ volume capability for the "Société des eaux de Marseille" finished in July 1958, Fig.4. This solution is slightly different from the previous ones. The support of the reservoir is solved in the same way with a brick masonry wall truncated cone shaped. The bottom of the vat presents a different solution, a reinforced concrete vault with the shape of a torus whose internal edge is supported by the central chimney and whose external edge is supported by the brick masonry wall. This edge is the rest of the external reservoir wall. This wall is solved in the same way as in the previous project. The cover consists in a series of timber vaults supported by concrete beams.

4 DISCUSSION

Torroja made many projects using this construction system, but only one was built in Madrid. The reservoir still exists but is not working. In the description made by Torroja some questions are not defined. The reservoir wall is supposed to be hinged on the bottom of the vat and no connector was designed between the bottom vault and the wall. In the analysis, only membrane tensions had been taken into account and no bending moment had been considered. So, the connection between the wall and the bottom is reduced to a channel in the bottom vault where the reservoir wall started to be built. The study of the existing reservoir can show if some reinforcement is needed at this point.

In analysis neither creeping nor retraction were considered. A study considering the strain effects in concrete over the years needs to be done in order to ensure that the concrete maintains its compression and can be impermeable.

The success of the construction depends greatly on the need to be very careful with the speed with which the injection is made. A control of the time the injection needs to set is necessary and the speed of the injection process depends on the mortar setting time. Also, the construction needs to be done without interruptions in order to guarantee a similar level of pressure in the external reinforced brick layer.

5 CONCLUSION

Eduardo Torroja was interested in the definition of new methods of construction. After his journey to South America in 1952, when he came back to Spain, he started some research into the possibilities of using brick masonry in the construction of shell structures. It is not clear if Torroja met Eladio Dieste [Ochsendorf 2003] on his travels but, at the time when Dieste began to build his structures with reinforced masonry, Torroja started his research looking for new possibilities for the use of timber vaults, [Antuña 2005]. A new way to build masonry works that would improve their qualities including the possibility of prestress, was an important advance in construction techniques. The new brick masonry work proposed made it possible to build reservoirs saving money since it is not necessary to pay for an expensive patented system. The project shown was finished in 1957 and, during the following four years until his death, Torroja designed five reservoirs using the same system, which fact demonstrates how he thought that the system was a real alternative to prestressed concrete. After his death none of his followers showed an interest in continuing the research in this field and no progress was made.

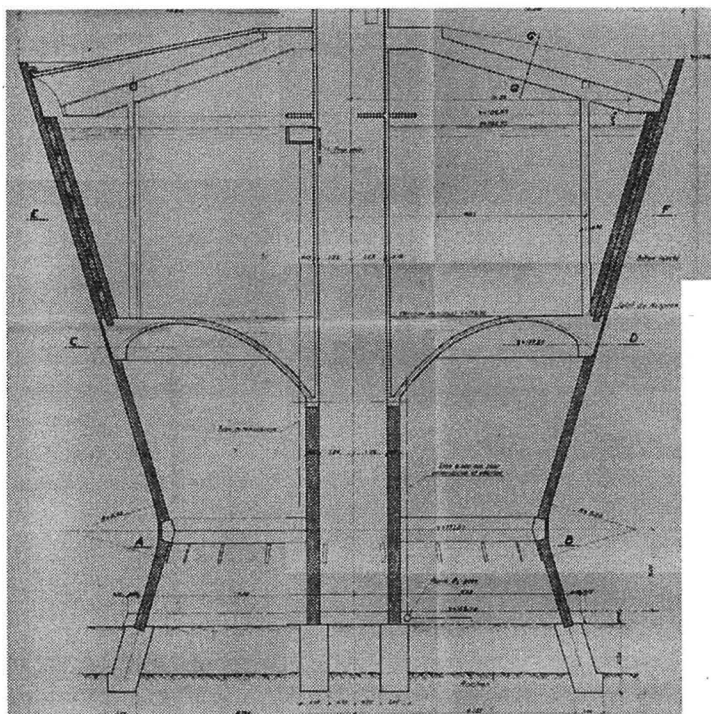


Figure 4. Cross section of the project for the reservoir for the “Société des eaux de Marseille.” It is a 2000m³ capacity reservoir to be built in Marseille. The organisation is similar to the Fedala reservoir, with the difference in the way the reservoir wall is made.

Now, when we know that thousands of millions of people have no access to water, and one of the first works made in emergency zones is to guarantee the water supply, it is of interest to develop construction systems that are economical and not highly technological, like this one proposed by Torroja fifty years ago.

ACKNOWLEDGMENTS

Eduardo Torroja worked in his own Technical Office from 1927 until his death in 1961. The documents concerning the projects he made are conserved in the files of his own office. After 1961, all the documents were taken to the engineering company directed by his son, also an engineer, José Antonio Torroja. I want to thank him for allowing me to consult these documents. Now, the Torroja file is in the “Centro de Estudios Históricos de Obras Públicas y Urbanismo” (CEHOPU) in Madrid and can be consulted freely. I want to thanks to the CEHOPU for the permission of use the images showed in this paper.

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